RTI INTERNATIONAL | Memorandum

RTI International
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To: California Integrated Waste Management Board

From: RTI International

Subject: Evaluation of Existing Municipal Solid Waste/ Life Cycle Assessment Tools

This memorandum contains RTI's results from the "Evaluation of Existing Municipal Solid Waste/ Life Cycle Assessment (MSW/LCA) Tools" as part of Task 4 of the *LCA of Organic Diversion Alternatives and Economic Analysis of Greenhouse Gas Reduction Options* project. To complete the tools evaluation, RTI identified relevant MSW/LCA tools and prepared a matrix that presents information on selected evaluation criteria for each of the tools. Consistent with the objectives of this work, emphasis was made on evaluating and comparing greenhouse gas (GHG) related estimation methodologies used in the different tools when modeling alternatives for organic waste management. This memorandum is organized in the following sections:

- **Section 1—Background**, describes the objectives of this evaluation in the context of the study;
- **Section 2—MSW/LCA Tools Identification**, describes the research and selection process of the tools that were evaluated;
- **Section 3—MSW/LCA Tools Evaluation**, explains the evaluation criteria and presents RTI's results after reviewing each tool against the selected criteria; and
- **Section 4—Conclusions and Recommendations**, uses the results presented under Section 3 to provide options for moving forward with a California specific LCA tool that focuses on modelling GHG emissions from organic diversion alternatives.

Section 1—Background

The California Integrated Waste Management Board (hereafter referred to as the Board) estimates that organics comprise approximately 73% of the State's MSW stream, including food scraps, yard trimmings, wood waste, and mixed paper. This statistic established organics management as a top priority for the Board. Organic waste is also important in the context of GHG emissions and climate action plans because it creates methane in landfills, which are the largest source of anthropogenic methane emissions in the United States.

The RTI International Team (including subcontractors R.W. Beck, Matthew Cotton, and Sally Brown) is assisting the Board in its efforts to achieve GHG emission reductions while striving toward zero waste and promoting sustainability by analyzing alternatives for the management of the organic fraction of MSW. The study will provide data and information to the Board to assist in considering and developing policies for organics waste management efforts in coming years, including such controversial issues as the role of conversion technologies and the use of organic waste as alternative daily cover.

This study will be completed in 15 tasks as described in the Board's Statement of Work (SOW). These tasks are grouped by the RTI Team into the following project parts:

- Part I—Communication and Workplan
- Part II—Life Cycle Assessment
- Part III—Economic Analysis
- Part IV—GHG Tool and Final Report

The goals/objectives of Part II Life-Cycle Assessment are to, using the LCA approach, identify and quantify (to the fullest extent possible) GHG emissions and the emissions reduction potentials associated with implementing defined organic diversion alternatives. The RTI Team's approach to the LCA includes leveraging RTI's in-house MSW DST for modeling waste management activities (e.g., collection, transfer, separation, preprocessing, composting, conversion, and land disposal) and to create a California specific peer-reviewed tool that will be used to quantify GHG emission reductions for organic diversion strategies.

Task 4—Life Cycle Assessment Screening Phase under Part II of the study includes the evaluation of existing MSW/LCA tools. A number of tools have been developed world-wide to evaluate the environmental (and sometimes cost) impacts associated with solid waste management. For this task, RTI identified existing tools, gathered key information about methods and data employed, reviewed the tools against defined criteria that are important to the Board and its goals for GHG emissions reduction and organics management, and provided conclusions and recommendations about what might be particularly useful features of a California-specific LCA/GHG tool.

Section 2—MSW/LCA tools identification

The International Expert Group (IEG) for LCA applications to MSW is currently evaluating and comparing existing MSW/LCA tools and RTI actively participants in the group. RTI used information already collected by the IEG to create the list of MSW/LCA tools of interest for this project. The information from the IEG was supplemented with the results of internet searches and available information about each tool. Environment Canada also has been reviewing MSW/LCA tools in the context of GHG modeling. However, their evaluation is not currently available.

Fourteen MSW/LCA tools were identified as of potential interest and of those four were screened out by not using a life cycle assessment approach. The following list presents the selected tools:

- IWM (Integrated Solid Waste Management tool)
- ORWARE (Organic Waste Research)
- LCA-IWM (Life Cycle Assessment-Integrated Waste Management)
- IWM-2
- WASTED (Waste Analysis Software Tool for Environmental Decisions)
- EASEWASTE (Environmental Assessment of Solid Waste Systems and Technologies)
- WRATE (Waste and Resources Assessment Tool for the Environment)
- WISARD (Waste-Integrated Systems for Assessment of Recovery and Disposal)

- WARM (Waste Reduction Model)
- MSW DST (Municipal Solid Waste Decision Support Tool)

The four tools initially identified but not included in the screening are:

- MIMES/WASTE or MWS (Municipal Waste Management Systems tool)
- AWAST (Tool to Aid the Management and European Comparison of Municipal Solid Waste Treatment Methods for a Global and Sustainable Approach)
- SWIM (Solid Waste Integrated Management Model)
- EUGENE

MIMES/WASTE and AWAST offer a systems engineering approach and focus on process design, but do not use a life cycle approach. Similarly SWIM and EUGENE do not use a life cycle approach. SWIM evaluates the relationship between the demand and supply of waste management systems; and between the environmental and economic impacts and the types of the supply system provided for a given demand. EUGENE is an optimization, process oriented model based on the mixed-integer programming paradigm. Different from linear programming in which variables can be either integers or rational numbers, mixed-integer programming is used when some of the variables are required to be integers.

The Board had also expressed interest on evaluating the CACP (Clean Air and Climate Protection) Software developed by ICLEI (International Council for Local Environmental Initiatives) and STAPPA/ALAPCO (the State and Territorial Air Pollution Program Administrators and the Association of Local Air Pollution Control Officials) and the CENTURY model developed by the Natural Resources Ecology Laboratory at Colorado State University. Despite not being an LCA tool, the use of the CACP Software for the waste sector allows estimating GHG emissions for the decomposition of waste under a variety of disposal scenarios including landfilling, open dumping, controlled incineration, open burning, and composting. The CENTURY model specializes on modeling plant-soil nutrient cycling, which could be useful to approximate the carbon sequestration potential of composting and mulching products applied to land. This model is currently used by EPA to approximate soil carbon sequestration associated with compost product application to land.

Section 3—MSW/LCA Tool Evaluation Criteria and Results

Each of ten MSW/LCA tools included in the evaluation was reviewed against selected criteria. The criteria were selected according to the objectives of this study, which include the development of a California specific LCA/GHG tool that allows modeling of different organics diversion alternatives and associated GHG emissions and sequestration. The following is the list of evaluation criteria and the rationale behind their selection:

- **Owning Organization**: this is the organization that developed/sponsored/maintains the tool, which usually corresponds to the organization holding intellectual property rights for the tool. Information about the owning organization could be indicative of the purpose of the model. For example, a model built by the recycling industry may emphasize recycling more than other MSW management alternatives.

- **Waste Streams Included**: this criterion is intended to list the waste streams considered by the tool. A tool that allows greater detail in the definition of the organic waste streams could be very useful for the purposes of this study. For example, a tool that differentiates paper, yard waste, and food waste categories.

- **Waste management alternatives included**: this criterion is intended to list the waste management alternatives considered in each tool. A tool that includes conventional (e.g., recycling and composting) and non-conventional/emerging technologies for MSW management such anaerobic digestion, gasification, pyrolysis, and hydrolysis are of additional interest given the scope of the project.

- **Geographic scope:** this criterion refers to the representativeness of the default data included in each tool. This study aims at modelling MSW management under California conditions. Therefore, a tool that already includes data representative of the United States and/or California, particularly to model the energy requirement of the systems, could be more useful than others. In general, tools allow using user defined data instead of the default data, but some tools are more flexible than others on the number user defined inputs.

- **Parameters reported:** life cycle inventory (LCI) results could be reported in terms of energy, emissions (air, water, and land), and cost. Most tools report energy and emissions to air and water and not all of them report emissions to the land and waste management costs. Cost information in particular could be very useful for the economic analysis, Part III of this study. Parameters reported of interest include GHG emissions from pre-combustion and combustion sources. Most models track and report methane (CH_4) and carbon dioxide (CO_2) emissions, but some models do not report nitrous oxide (N_2O) emissions and/or differentiate between CO2 fossil and biogenic (from organic sources). This differentiation is important because according to IPCC (Intergovernmental Panel on Climate Change) guidelines carbon equivalents and credits as potential benefits from a given waste management process should not include CO_2 biogenic emissions.

- **Environmental impacts reported**: in addition to providing LCI results some models translate those results to environmental impacts in an attempt to improve communication and facilitate decision making. Reporting environmental impacts involve translating and aggregating the results from the LCI into environmental impacts and/or equivalency scores. The environmental impact scores are given in a unit corresponding to the impact type, for example, CO_2-equivalents for global warming potential. Equivalency scores are conversion factors that allow the user to convert the inventory results into every day equivalents, for example, the amount of electricity used by an average home for a year.

- **Methodology for estimating GHG emissions by alternative:** this criterion refers to the type of data (measurements vs. assumptions) and models (mechanistic vs. empiric) used to estimate the emissions associated to each waste management process. It also refers to the emissions sources and offsets consider in the estimation of GHG emissions. A detailed list of emission sources and offsets considered for each process and tool can be found in Table 2. GHG Sources and Offsets by Processes Considered in Each Tool.

- **Inclusion of beneficial offsets:** this criterion indicates whether a tool estimates beneficial offsets from the waste management processes. Beneficial offsets are associated to energy, emissions, and cost savings. Examples include virgin material offsets from recycling and energy offsets from landfills with energy recovery.

- **Modelling mode:** tools that can be run in optimization mode will be very useful to design optimize waste management systems according to certain environmental and economic goals. Alternatively, tools that can be run in simulation mode are very useful to evaluate the performance of a given MSW management system. This study aims at obtaining LCA results from the simulation of different organic diversion alternatives.

- **Level of peer review:** this criterion seeks to confirm the scientific validity of the methodology and data used in a tool. For the purposes of this study, only tools that have undergone peer review will be for consideration when developing a California specific MSW/LCA tool.

- **Ease of use:** When evaluating the selected tools against this criterion, the RTI team asked the following questions: 1) How easy is to understand the tool from the available documentation? 2) Is there a user manual available? 3) Does the tool have a GUI (graphical user interface)? With few exceptions (WRATE, WISARD, WARM, and MSW DST) the electronic versions of the selected tools were not downloaded or tested. Therefore, the evaluation against this criterion relied on observations from the available documentation.

- **Availability:** this criterion refers to whether the tool has open source code, is publicly available free of charge or with a charge or per subscription.

- **Software:** this criterion is important to determine how accessible the model will be for the general user. Models that were identified to use software outside of the MS Office platform could be restrictive for the general user.

Available documentation (journal publications, background documents, and user manuals) was used to evaluate the tools against the described criteria. With few exceptions (WRATE, WARM and MSW-DST), the electronic versions of the selected tools were not downloaded or tested. The evaluation of the methodology for estimating GHG emissions by alternative was limited to the available documentation.

Table 1 presents the overall results of the tool evaluation. In most cases, only a description of the emissions sources and offsets was found and included in Table 2.

Additional insight on the characteristics of the selected tools is provided by Diaz and Warith (2006), which describes the development of the WASTED model and also reviews the IWM model, the WARM model, and ORWARE. This document compares the results of these models and found that the IWM model, the WARM model, and ORWARE lack user friendliness or model flexibility. For example, ORWARE uses relatively specialized software: Matlab, and IWM and WARM only allow limited user modification of model parameters (such as landfill carbon sequestration, virgin- to recycled ratio content in different materials, etc.)

Diaz and Warith (2006) also describes how IWM's compost model predicts net emissions, while WARM and WASTED show CO_2 credits (avoided emissions). "This might be because these two models consider a storage factor of 0.183 tonne of CO_2 per tonne of organic waste (EPA, 2002), while the IWM model assigns a displacement factor of 10% (Haight, 2004)". Referring to a City of Toronto Case Study[1], Diaz and Warith (2006) stated that "in general, the IWM model is the most conservative of the three: it predicts the least amount of CO_2 credits from this scenario. In contrast, WARM is the most optimistic and predicts the most emissions credits. The results from WASTED fall between them, estimating 37% less credits than WARM and 19% more than the IWM model."

CACP Software

CAPC is a tool whose main functionality is the estimation of GHG from different private or public sectors including residential, commercial, industrial, waste, and transportation. In addition to this emissions inventory capability, the software can be used to project emissions by estimating changes produced by different control measures. When working with the waste sector, CACP accounts for landfill carbon sequestration and recycling forest carbon sequestration. It allows the user to select one of two methods for calculating GHG emissions: (1) the methane commitment method, and (2) the waste-in-place method. The methane commitment method quantifies the net lifetime GHG emissions from waste disposed of in the active year. Although each site/practice will emit gases over time, the methane commitment method attributes all future emissions to the year in which the waste was produced. On the other hand, the waste-in-place method calculates methane emissions occurring in the active year as the result of the accumulated waste already interred in the landfills.

Both methodologies rely on the methane recovery factor. The main advantage of using the methane commitment method is that it provides results that are comparable to the estimated emissions avoided by reduce, reuse, and recycle programs. For example, reducing the amount of waste produced avoids all emissions that would have been released over the lifetime of the waste's decomposition. Therefore, it is easier to account for all of the emissions that will be released and all of the emissions that will be avoided in one year. This is the default method used in the software.

Although not particularly sensitive to reduce, reuse, and recycle waste programs the Waste-In-Place method is appropriate for approximating the amount of landfill gas released by waste already interred. This is particularly useful in quantifying the emissions from closed landfills, or estimating the gas available for flaring, heat recovery or power generation projects.

The following are additional characteristics of the CACP Software corresponding to some of the evaluation criteria used for the LCA tools. This information was obtained from ICLEI and STAPPA/ALAPCO (2003).

- <u>Waste streams included</u>: CACP includes different paper categories, glass, ferrous metals, aluminum, plastics, food waste, and yard waste.

[1] For this case study the three models were used to simulate waste management practices in the city and under a scenario in which only parameters corresponding to waste generation and composition, electric energy grid mix, landfill type, distance to landfill, and precipitation were set to be city specific.

- Waste management alternatives included: CACP includes source reduction, recycling, composting, incineration, landfill disposal, open dumping, and open burning.

- Geographic scope: STAPPA/ALAPCO (2003) states that the software can be customized for application in any country. Most of the default data is United States data (e.g., GHG emission coefficients are based on U.S.EPA's AP-42 emission factors).

- Parameters reported: the software only estimates emissions to air.

- GHG emissions tracked/reported: the software tracks CO_2 fossil, CH_4, and N_2O and reports them as carbon equivalents.

- Inclusion beneficial offsets: it only includes benefits from materials recycling.

- Modeling mode: CACP can only be run in simulation mode

- Level of peer review: the documentation reviewed did not describe the level of peer review.

- Ease of use: it has a GUI available for data entry, to run the model, and to output the results.

- Availability: the software is available for free after registering at http://www.cacpsoftware.org/.

- Software: it has a VB GUI.

CENTURY Model GHG Estimation Methodology

CENTURY is an agro-ecosystem model designed to evaluate the effects of management practices (cropping system rotations, tillage practices, fertilization, irrigation, grazing, and harvest methods) and global change on productivity and sustainability. The model simulates the long-term dynamics of Carbon (C), Nitrogen (N), Phosphorus (P), and Sulfur (S) for different Plant-Soil Systems. It can simulate the dynamics of grassland systems, agricultural crop systems, forest systems, and savanna systems. "The grassland/crop and forest systems have different plant production sub-models which are linked to a common soil organic matter sub-model. The savanna model uses the grassland/crop and forest subsystems and allows for the two subsystems to interact through shading effects and nitrogen competition. The soil organic matter sub-model simulates the flow of C, N, P, and S through plant litter and the different inorganic and organic pools in the soil. "(Metherell et al., 1993)

The model runs using a monthly time step. Major input variables for the model include (1) monthly average maximum and minimum air temperature, (2) monthly precipitation, (3) lignin content of plant material, (4) plant N, P, and S content, (5) soil texture, (6) atmospheric and soil N inputs, and (7) initial soil C, N, P, and S levels.

Output from the model are usually expressed as (1) grams of C, N, P, or S per meter square in soil organic matter, (2) grams C, N, P, or S per meter square in plant material, and (3) grams N, P, or S per meter square in mineral pools.

The soil organic matter (SOM) submodel in CENTURY could be useful when designing or refining a methodology to estimate soil carbon sequestration from compost application. This is a multiple compartments model where each compartment or pool has a distinctive potential decomposition rate. There are three pools: active, slow and passive, above and belowground litter pools, and a surface microbial pool which is associated with decomposing surface litter.

The decomposition of both plant residues and SOM are assumed to be microbially mediated with an associated loss of CO_2 as a result of microbial respiration. Decomposition products flow into a surface microbe pool or one of three SOM pools. The active pool represents soil microbes and microbial products and has a turnover time of months to a few years depending on the environment and sand content. The surface microbial pool transfers material directly into the slow SOM pool. The slow pool includes resistant plant material derived from the structural pool and soil-stabilized microbial products derived from the active and surface microbe pools. It has a turnover time of 20 to 50 years. The passive pool is very resistant to decomposition and includes physically and chemically stabilized SOM and has a turnover time of 400 to 2000 years. The decomposition products which enter the passive pool could be used to define the amount of carbon that gets sequestered into the soil.

The following are additional characteristics of the model.

- Software: the model is designed in Fortran.
- Ease of use: users need familiarity with Fortran to run the model. The model is well documented.
- Availability: the software is available for free at http://www.nrel.colostate.edu/projects/century/.

Section 4 – Conclusions and Recommendations

The results of this review are particularly useful to identify tools that model different organics diversion alternatives including non-conventional/emerging technologies such anaerobic digestion, gasification, pyrolysis, and hydrolysis. These tools could be used to supplement RTI's MSW DST capabilities in designing a California-specific MSW/LCA tool that focuses on organics diversion alternatives. To this regard, gasification and pyrolysis were the only emerging technologies considered by few of the tools reviewed. WISARD and WRATE can be used to model gasification and pyrolysis and EASEWASTE can also be used to model gasification.

Key aspects to consider for the development of a California-specific MSW/LCA tool include (1) ability to track and report GHG emissions (CO_2, CH_4, and N_2O) from pre-combustion and combustion processes, (2) coverage of GHG sources and sinks, (3) use of widely accepted methodologies to estimate GHG emissions and beneficial offsets, and (4) flexibility to model different organics waste categories. The following conclusions are developed around these key aspects.

1. **Ability to track and report key GHG emissions (CO_2, CH_4, and N_2O) for all life cycle aspects.** With few exceptions, most tools reviewed track and report CO_2, CH_4, and N_2O emissions and estimate carbon equivalents. ORWARE only includes process-related emissions and not other life cycle emissions such as those associated with energy production. WARM tracks process and other life cycle emissions of all GHG, but reports them as carbon equivalents. Reporting emissions for each of the GHG is important since this helps prioritizing emission reduction efforts.

2. **Coverage of GHG sources and sinks**. Most of the tools consider process and other life cycle GHG emission sources. However, the inclusions of emission sinks, which include forest and soil carbon sequestration, vary across different tools. For example, a few tools (i.e., IWM, LCA- IWM, WASTED, and WARM) consider soil carbon sequestration as a beneficial offset from composting. Furthermore, most tools do not present enough documentation as to evaluate the scientific rigor of their methodologies. To this regard, the CENTURY model seems to offer a comprehensive and rigorous methodology that could potentially be used for modeling soil carbon sequestration, or using information already developed for EPA's WARM. Since composting could be one of the main organic diversion alternatives, soil carbon sequestration methodologies and related data would be very helpful for developing the California-specific tool. The tool should allow the user deciding whether carbon sequestration will be considered or not since some forms of carbon sequestration (e.g., landfilling of biodegradable waste) are still debated and have not been accepted under the Kyoto Protocol.

3. **Use of widely accepted methodologies to estimate GHG emissions and beneficial offsets.** Tools that use peer-reviewed methodologies and/or follow the guidelines of the IPCC are recommended for consideration when designing a California-specific tool. In general, the degree to which each of the tools has been peer-reviewed was not well documented. Most tools are either described in a peer review journals or their documentation mention to have undergone peer review. Therefore, further research about the level of peer- review will be needed for tools that could be included in the development of a California-specific tool. This would also help selecting between tools that seem to have similar capabilities. For example, according to Diaz and Warith (2006) in estimating carbon sequestration from compost application WARM and WASTED consider a storage factor of 0.183 ton of CO_2 per ton of organic waste while the IWM model assigns a displacement factor of 10%. Additional analysis would be required to determine which estimation methodology would be more appropriate for the purposes of this study. Similarly, LCA-IWM, IWM-2, WISARD, and WRATE estimate fertilizer offsets from compost application. Variations in the substitution ratios and the fertilizer emissions data across these tools has to be better studied.

4. **Flexibility to model different organics waste categories.** GHG emissions vary significantly depending on the amount and type of organic material in the waste stream. For example, landfill disposal of organics is the largest source of methane and food waste is the organics category with the highest methane yield. All the tools reviewed model different paper and yard waste categories and allow modeling food waste as a separate

category. EASEWASTE goes as far as to differentiate between vegetable and animal food waste and to allow entering animal excrements as a separate waste category.

References

Dalemo, M., U. Sonesson, A. Bjorklund, K. Mingarini, B. Frostell, H. jonsson, T. Nybrant, J- O. Sundqvist, and L. Thyselius. 1997. ORWARE- A Simulation model for Organic Waste Handling Systems. Part 1: Model Description. Resources Conservation and Recycling. Vol 21, p. 17-37.

Den Boer, E, J. Den Boer, and J. Jager. 2005. Waste Management Planning and Optimization, Handbook for Municipal Waste Prognosis and Sustainability Assessment of Waste Management Systems. Stuttgart, Germany.

Diaz, R. and M. Warith. 2006. Life Cycle assessment of municipal solid wastes: development of the WASTED model. Waste Management 26, 886-901.

EPIC (Environment and Plastics Industry Council), University of Waterloo, CSR (Corporations Supporting Recycling), and Environment Canada. 2004. Integrated Waste Management Tools: "Measuring the Environmental Impact of Waste Management Systems". Brochure available at: http://www.iwm-model.uwaterloo.ca/english.html . April

ICLEI (International Council for Local Environmental Initiatives) and STAPPA/ALAPCO (the State and Territorial Air Pollution Program Administrators and the Association of Local Air Pollution Control Officials). 2003. Clean Air and Climate Protection Software Users' Guide. Available at: http://www.cacpsoftware.org/ . June

Kirkeby J. T., Harpa Birgisdottir, Gurbakhash Singh Bhander, Michael Hauschild, and Thomas H. Christensen. 2007. Modelling of environmental impacts of solid waste landfilling within the life-cycle analysis program EASEWASTE. Waste Management 27 961- 970.

Kirkeby J. T., Harpa Birgisdottir, Trine Lund Hansen, Thomas H. Christensen, Gurbakhash Singh Bhander and Michael Hauschild. 2006. Environmental assessment of solid waste systems and technologies: EASEWASTE. Waste Management Research 24(3) 3-15.

Metherell A. K., Laura A. Harding, C. Vernon Cole, and William J. Parton. 1993. CENTURY Soil Organic Matter Model Environment, Century Manual and Technical Documentation. Prepared for the Great Plains System Research Unit, USDA-ARS, Fort Collins Colorado. Technical Report No. 4. Available at: http://www.nrel.colostate.edu/projects/century/

Price Waterhouse Coopers. 2007. Wisard Reference Guide. Available at http://www.ecobilan.com/uk_wisard.php. October

Procter & Gamble (P&G). 2005. IWM-2 an LCI Computer Model for Solid Waste Management, Model Guide. Available at: http://www.scienceinthebox.com/en_UK/sustainability/solid_waste_management_en.html#six

RTI International. 2007. Personal communication, Keith Weitz and Alexandra Zapata. October 30.

Sonesson, U., M. Dalemo, K. Mingarini, and H. jonsson. 1997. ORWARE- A Simulation model for Organic Waste Handling Systems. Part 2: Case Study and Simulation Results. Resources Conservation and Recycling. Vol 21, p. 39- 54.

UK Environment Agency. 2007. WRATE Version 1.0.1.0, Demonstration Version. Available on CD by request. January 4.

U.S.EPA (Environmental Protection Agency). 2006. *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks*. 3rd Edition. EPA530-R-06-004. Available at: http://www.epa.gov/climatechange/wycd/waste/calculators/Warm_home.html . September

Table 1. Matrix of Evaluation Criteria and Selected MSW/LCA Tools.

Tool Name		IWM (Integrated Solid Waste Management tool)	ORWARE (Organic Waste Research)	LCA- IWM (Life Cycle Assessment-Integrated Waste Management)	IWM- 2	WASTED (Waste Analysis Software Tool for Environmental Decisions)	EASEWASTE (Environmental Assessment of Solid Waste Systems and Technologies)	WISARD (Waste-Integrated Systems for Assessment of Recovery and Disposal)	WRATE (Waste and Resources Assessment Tool for the Environment) [1]	WARM (Waste Reduction Model)	MSW- DST (Municipal Solid Waste- Decision Support Tool)
Owning organization		EPIC (Environment and plastics industry council) & CSR (Corporations supporting recycling), The University of Waterloo built the model and manages its website.	Swedish Waste Research Council (AFR)	The European Commission	Procter & Gamble	Natural Sciences and Research Council of Canada (NSERC) and Ryerson University	Technical University of Denmark	Ecobilan or Ecobalance, a private consulting company from France owned by Price Waterhouse Coopers	UK Environment Agency	U.S.EPA, Office of Solid Waste	RTI International
Waste streams included	Paper	Allows definition of paper categories	Allows definition of paper categories	Allows definition of paper categories	Allows definition of paper categories	Allows definition of paper categories	Allows definition of paper categories such milk cartons, juice cartons with aluminum foil, kitchen tissues, dirty and clean paper	Allows definition of paper categories	Allows definition of paper categories	Allows definition of paper categories	Allows definition of paper categories
	Glass	yes	no	yes	yes	yes	yes	yes	yes	yes	yes
	Ferrous metals	yes	no	yes	yes	yes	yes	yes	yes	yes	yes
	Aluminum	yes	no	yes	yes	yes	yes	yes	yes	yes	yes
	Plastics	yes	no	yes	yes	yes	yes	yes	yes	yes	yes
	Food waste	yes	yes	yes	yes	yes	Makes distinction between vegetable and animal food waste	yes	yes	yes	yes
	Yard waste	yes	yes	yes	yes	yes	yes	yes	yes	yes	Yes, branches, leaves, and grass

Tool Name		IWM (Integrated Solid Waste Management tool)	ORWARE (Organic Waste Research)	LCA- IWM (Life Cycle Assessment- Integrated Waste Management)	IWM- 2	WASTED (Waste Analysis Software Tool for Environmental Decisions)	EASEWASTE (Environmental Assessment of Solid Waste Systems and Technologies)	WISARD (Waste- Integrated Systems for Assessment of Recovery and Disposal)	WRATE (Waste and Resources Assessment Tool for the Environment) [1]	WARM (Waste Reduction Model)	MSW- DST (Municipal Solid Waste- Decision Support Tool)
	Other waste	yes, textiles, rubber, diapers, kitty litter, tires, home renovation wastes, white goods, and household hazardous waste. Diversion of these waste streams is not considered.	no	yes, clothes, textiles, soil, stones, street cleaning residues, septic tanks sludge, waste from electrical and electronic equipment, bulky waste, and hazardous waste.	yes, textiles, fine materials, leather, rubber, and wood.	yes, miscellaneous waste that do not belong to the other categories. Examples are rubber, leather wastes, and construction debris.	yes, animal excrements, napkins and tampons, cotton sticks, other cotton, wood, textiles, shoes, leather, rubber, cigarette buts, vacuum cleaner bags, soil, rocks, stones, gravel, ash, ceramics, cat soil, and batteries.	yes, textiles, batteries, fines	yes, textiles, absorbent hygiene products, wood, fines, waste electrical and electronic equipment, specific hazardous household	yes, clay bricks, concrete, copper wire, fly ash, tires, carpet, PCs, MDF, dimensional lumber	yes, miscellaneous, either organic or inorganic, waste that do not belong to the other categories.
Waste management alternatives included	Source reduction	no	no	no	no	no	no	no		yes	yes
	Collection	yes	no	yes	yes	yes	yes	yes	yes	yes	yes
	Recycling	yes	no	yes, but only recycling of source separated material.	yes	yes	yes	yes	yes	yes	yes
	Composting	yes	yes, three types of composting are included: home, windrow, and reactor. The differences modeled are energy consumption for handling the compost, the possibilities to have compost gas cleaning and the fact that in small-scale home composting there are lower percentages of heavy metals.	yes, but only composting of separately collected organics including yard waste.	yes	yes	yes	yes	yes [2]	yes	yes, yard waste or mixed waste composting

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	Anaerobic digestion	yes	yes	yes, it includes a compost maturation process and only accepts separately collected organics.	yes, it includes a compost maturation process.	no	yes	yes	yes, it includes a compost maturation process. [2]	no	off-line
	Land Application	yes, yard waste only	yes	no	no	no	yes	no	no	no	yes
	WTE- Incineration	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
	Gasification	no	no	no	no	yes	no	yes	yes	no	off-line
	Pyrolysis	no	no	no	no	no	no	yes	yes	no	off-line
	Landfill Disposal	yes, fly ash is managed at a hazardous waste landfill or sent to a fly ash user. Bottom ash is managed at a MSW landfill.	yes, three landfills are included: MSW landfill, ash landfill, and slag landfill.	yes, it includes an/aerobic mechanical biological pretreatment of residuals [3]	yes	yes, it includes a bioreactor landfill.	yes	yes	yes	yes	Yes, including mixed waste, bioreactor, and ash landfills
	Transportation	yes, Transportation emissions are presented separately from the emissions from different processes.	yes	yes	yes	yes, transportation emissions are presented separately from the emissions from different processes.	no	yes	yes	yes, transportation emissions are added to the results from model processes (e.g., the results from recycling include the emissions from the transportation of waste to the MRF).	yes

Tool Name		IWM (Integrated Solid Waste Management tool)	ORWARE (Organic Waste Research)	LCA- IWM (Life Cycle Assessment- Integrated Waste Management)	IWM- 2	WASTED (Waste Analysis Software Tool for Environmental Decisions)	EASEWASTE (Environmental Assessment of Solid Waste Systems and Technologies)	WISARD (Waste- Integrated Systems for Assessment of Recovery and Disposal)	WRATE (Waste and Resources Assessment Tool for the Environment) [1]	WARM (Waste Reduction Model)	MSW- DST (Municipal Solid Waste- Decision Support Tool)
Geographic scope		Designed for use in Canadian municipalities. Data were derived from sources such as governments in Canada, the U.S., and Europe together with other material published in recognized journals. Some parameter values can be overwritten using the GUI.	The sewage plant model and data follows the layout of the Kungsangen plant in Uppsale, Sweden. The incineration model is based on the incineration plant of Uppsala Energi AB in Uppsala, Sweden in 1993 and is not directly applicable to any other incineration plant. The landfill model describes a general Swedish landfill. The compost model is based on empirical relations and measurements of swedish conditions.	Modeled waste management technologies present state-of-the-art in Western European countries. The data stem from the Western European countries. The model offers some degree of flexibility to modify the technologies and the data.	Modeled waste management technologies present state-of-the-art in Western European countries. The data stem from the Western European countries. The model only uses default data when user-defined data are not provided.	It uses emissions data published by the U.S.EPA, the Danish EPA, and the IVM model. In order to ensure that the results are representative of the case being evaluated, it is recommended that site-specific parameters be used whenever possible.	Default data reflect Danish conditions. The model consists of a set of databases and modules, which together define a scenario of a solid waste system. Modules used in a scenario are taken from the database and copied into the scenario. Thereafter, data input can be modified by the user and the database can be extended continuously with external materials and processes, as well a with waste treatment, recovery and disposal technologies as needed for a specific assessment.	The tool is customizable according to specific needs (region, processes specifications…) In addition; users can collect and create their own data sets either directly or by adapting from the data sets provided. The default datasets and process designs reflect European conditions. The tool has been customized to simulate waste management scenarios from UK, France, and New Zealand.	The data is sourced from the UK operating and pilot plant or from European or other international plant where UK data is not available. The software is limited to the chemical analysis provided for waste categories defined in the Environment Agency's waste analysis research program. The tool can be used for commercial and industrial waste streams if they are similar in composition to the municipal waste streams.	US	Default data and processes design are representative of US conditions, but they can be modified to model different conditions. For example, the tool is currently being used to simulate and optimize waste management systems in 9 different countries.
Parameters reported	Cost	no	no	yes	yes	no	No, a new version of EASEWASTE is currently being developed to include cost as well as a module to conduct sensitivity analysis.	yes	no	no	yes
	Energy	yes	yes	yes	yes	yes	no	yes	yes	yes	yes
	Emissions to air	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes (CO_2 fossil, CO_2 biogenic, CH_4)
	Emissions to water	yes	yes	yes	yes	yes	yes	yes	yes	no	yes

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	Emissions to land	yes	No, it only estimates the amount of residues returned to arable land.	yes	yes	no, it only estimates land loss as a result of landfill disposal.	yes	yes	yes	no	yes
GHG emissions tracked/reported	CO2 fossil	yes, assumed zero for composting scenarios	yes, for combustion emissions. No, for pre-combustion emissions	yes	yes	yes	yes	yes	yes	included; not reported separately	yes
	CH4	yes	yes, for combustion emissions. No, for pre-combustion emissions	yes	yes	yes	yes	yes	yes	included; not reported separately	yes
	N2O	no	yes, for combustion emissions. No, for pre-combustion emissions	yes	yes	Tracked, but not reported.	yes	yes	yes	included; not reported separately	No
Environmental Impacts reported		yes, as equivalency scores (power to supply x homes, emissions from x vehicles, or sewage from x people for one year).	no	yes, depletion of abiotic resources, climate change, human toxicity, photo-oxidant formation, acidification, and eutrophication.	yes, as equivalency scores (power to supply 1 home/year, emissions from 1 vehicle/year, or sewage from x people for one year).	yes, carbon equivalents. Nox emissions are not included in the total of CO2 equivalents since different nitrogen oxides compounds have different GHG impacts and they are not accounted for separately in the model.	yes, environmental impacts are expressed as potential for soil ecotoxicity, water ecotoxicity (acute and chronic), soil human toxicity, air human toxicity, water human toxicity, nutrient enrichment, photo-chemical ozone, acidification, and global warming.	yes, greenhouse effect, air acidification, stratospheric ozone depletion, photochemical oxidant formation, water eutrophication, and non-renewable source depletion.	yes, abiotic depletion, global warming, ozone layer depletion, human toxicity, fresh water aquatic ecotoxicity, marine aquatic ecotoxicity, marine sedimental ecotoxicity, terrestrial ecotoxicity, human toxicity, photochemical oxidation, acidification, and eutrophication.	For energy, equivalents expressed as reduction in annual passenger cars from roadway, barrels of oil, or gallons of gasoline	Greenhouse gas equivalents (MTCE)
Methodology for estimating GHG emissions by alternative		See Table 2	Liner and Static model, using yearly average approach. See Table 2 for additional information.	See Table 2	See Table 2	See Table 2	NR	See Table 2	[4]	Streamlined life-cycle used to create waste/waste management emission factors used in the model for comparative analysis of waste management options	[5]

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Inclusion beneficial offsets	Yes, from materials recycling and energy recovery processes.	Plant nutrient (nitrogen and phosphorous) utilization is considered.	Yes, from materials recycling, composting, anaerobic digestion, an/aerobic mechanical biological pretreatment of residuals, and energy recovery processes.	Yes, from materials recycling, composting, and energy recovery processes.	Yes, from materials recycling, composting, and energy recovery processes.	Yes, from materials recycling and energy recovery. No, from composting.	Yes, from materials recycling, composting, pyrolyisis, and energy recovery processes.	Yes, from materials recycling, composting, pyrolyisis, and energy recovery processes.	Yes, from materials recycling and source reduction, composting, and energy recovery processes.	Yes, from materials recycling and energy recovery. No, from composting.
Modeling mode – Simulation	Yes	Yes	Yes	Yes	yes	yes	yes	yes	yes	yes
Modeling mode – Optimization	no	no	no	no	no	NR	no	no	no	yes
Level of peer review	Has been peer reviewed by an independent panel of five reviewers.	Model description, case studies, simulation results, and validation results are published in a peer review journal (Resources, Conservation and Recycling)	No information was found.	No information was found.	Model documentation is published in a peer review journal (Waste Management).	Model documentation is published in a peer review journal (Waste Management & Research) and subsequent use of the tool for a case study is also published in a peer review journal (Waste Management).	Yes, data and methodology peer review was performed in 1999. Additional peer review was performed for the New Zealand WISARD model.	WRATE has followed a peer review process undertaken by an external independent reviewer to assess the relevance of the data, the methods used, the software functionality and included data, the modeling, the software and report transparency and the completeness against the goal and scope terms of the project. The review has been undertaken to ensure user confidence in the functioning of the tool and the underlying data.	No information was found.	Internal (EPA) and external peer reviews

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Ease of use	GUI available for data entry, to run the model, and to output the results. Each waste management alternative has its own screen as part of the GUI.	No information was found.	GUI available for data entry, to run the model, and to output the results.	GUI available for data entry, to run the model, and to output the results.	Results can be exported to an Excel spreadsheet.	The developers report that the model is user friendly, well-documented and flexible.	WISARD provides the user with an extensive range of reporting options (from tabular format to a wide variety of built in graphical options). Results can be exported in a text file. Then the user can display and compare results from different scenarios in Excel, PowerPoint, etc	Moderate-difficult to use GUI without a user manual. Demo version does not come with a user manual.	Available in on-line form or Excel spreadsheet; easy-to-use GUI	Low (difficult) for current version. Easier to use web version to be released in 2008.
Availability	http://www.iwm-model.uwaterloo.ca/english.html Available free of charge after registering.	No information was found.	http://www.iwar.bauing.tu-darmstadt.de/abft/Lcaiwm/Project/TheResults.htm Available free of charge.	http://www.scienceinthebox.com/en_UK/sustainability/solid_waste_management_en.html#six A demo can be downloaded free of charge.	No information was found.	NR	Available under license. WISARD is provided with a core set - 'Starter Kit' - of data. Additional data sets may be purchased by the user as appropriate. A demo version and documentation is available online at http://www.ecobilan.com/uk_wisard.php.	http://www.environment-agency.gov.uk/wtd/1396237/?version=1&lang=_e The Intellectual Property Rights for the software and data are exclusive to the UK Environment Agency. Consent must be obtained from the Environment Agency for use of the data in third party applications. The ecoinvent background data in the tool is exclusive to the Ecoinvent Centre. WRATE is sold as a single installation license.	Available free at http://www.epa.gov/climatechange/wycd/waste/calculators/Warm_home.html	Contact RTI. Web-based version to be released in 2008
Software	MS Excel 2000 with VB GUI	MATLAB/ SIMULINK	MS Excel with VB GUI	MS Excel with VB GUI	MS Excel with VB GUI. Allows users to modify almost all parameters used in a simulation.	NR	TEAM ("Tools for Environmental Analysis and Management" is a registered trademark of the Ecobilan Group) is the LCA software and calculation engine.	It uses the ecoinvent v1.2 database that is used to estimate the life cycle costs for the materials and energy that are used or recovered by processes.	On-line as web-based calculator or in MS Excel spreadsheet 5.0, 97, or 2000	MS Excel with VB GUI and CPLEX (optimization software). Web-based version to be released in 2008
Information source	EPIC, CSR, and Environment Canada, 2004	Dalemo et al., 1997	Den Boer et al., 2005	Procter & Gamble, 2005	Diaz and Warith, 2006	Kirkeby et al., 2006 Kirkeby et al., 2007	Price Waterhouse Coopers, 2007	UK Environment Agency, 2007	U.S.EPA, 2006	RTI International, 2007

Notes for Table 1:

NA: Not Applicable

NR: Not Reported

[1] It is a gate-to-gravel model.

[2] A mechanical pretreatment process precedes composting and anaerobic digestion for stability. The process is a shredding and screening stage (80 - 100 mm) with subsequent metals separation.

[3] An/aerobic mechanical biological pretreatment of residuals are alternatives to incineration that take place prior to landfill disposal to aid minimizing environmental impacts. LCA-IWM models these processes using the splitting concept in which first mechanical division of the waste takes place and a derived fraction of material is treated biologically under an/aerobic conditions.

[4] Electricity generation avoided is offset against an inventory of marginal national grid energy mixes (or a representative mix for independent devolved administrations or other countries, where available). Heat energy is offset against a gas combustion inventory with a thermal efficiency of 85%. Where recycled materials are substituted to provide the same function as a virgin material (e.g. shredded paper as a packaging material over polystyrene), materials are offset against the inventory for virgin material production for the typical material on the basis of functional equivalence. If the performance of the recycled material is different to that of the standard market material (e.g. more weight of paper is required to pack an item than the standard material) then a factor is used in the model to account for the difference. Apart from ensuring functional equivalence, the tool does not account for the environmental impacts of the functions of materials once recovered or recycled and incorporated into new products.

[5] Recycling relies on energy consumption GHG emissions data nets out GHG emissions avoided from recycling of specific items. Compost uses laboratory data plus energy consumption GHG emissions data. Combustion uses a stoichiometric approach and nets out GHG emissions avoided from the utility sector based on a user-defined grid mix of fuels. Landfill uses a first-order decay model and nets out GHG emissions avoided from the utility sector based on a user-defined grid mix of fuels.

Table 2. GHG Sources and Offsets by Processes Considered in Each Tool

MSW Management Strategy	GHG Sources	GHG Offsets				
	Pre-combustion and Combustion*[1]	Forest Carbon Sequestration	Soil Carbon Storage	Landfill Carbon Sequestration	Energy Savings	Virgin Materials Savings
Source reduction	NA	WARM	NA	NA	WARM	WARM
Collection	IWM, LCA- IWM, IWM-2, WASTED, EASEWASTE, WISARD, WRATE, WARM, MSW- DST	NA	NA	NA	NA	NA
Recycling	IWM, LCA- IWM, IWM-2, WASTED, EASEWASTE, WISARD, WRATE, WARM, MSW- DST	IWM, WARM	NA	NA	IWM, LCA- IWM, IWM-2, WASTED, EASEWASTE, WISARD, WRATE, WARM, MSW- DST	IWM, ORWARE, LCA- IWM, IWM-2, WASTED, EASEWASTE, WISARD, WRATE, WARM, MSW- DST
Composting	IWM, ORWARE, LCA- IWM, IWM-2, WASTED, EASEWASTE, WISARD, WRATE, WARM, MSW- DST	NA	IWM [4], LCA- IWM [2], WASTED [5], WARM [5]	NA	NA	LCA- IWM [3], IWM-2, WISARD, WRATE
Anaerobic digestion [6]	IWM, ORWARE, LCA- IWM, IWM-2, WISARD, EASEWASTE, WRATE, MSW-DST	NA	NA	NA	IWM, ORWARE, LCA- IWM, IWM-2, WISARD, EASEWASTE, WRATE, MSW- DST	LCA- IWM [3], IWM-2, WISARD, WRATE
Land Application	IWM, ORWARE, EASEWASTE, MSW- DST	NA	NA	NA	NA	NA
WTE- Incineration	IWM, ORWARE, LCA- IWM, IWM-2, WASTED, EASEWASTE, WISARD, WRATE, WARM, MSW- DST	NA	NA	NA	IWM, LCA- IWM, IWM-2, WASTED, EASEWASTE, WISARD, WRATE, WARM, MSW- DST	Any material recovery is included under recycling
Gasification	EASEWASTE, WISARD, WRATE, MSW-DST	NA	NA	NA	WASTED, WISARD, WRATE, MSW-DST	MSW- DST
Pyrolisys	WISARD, WRATE, MSW- DST	NA	NA	NA	WISARD, WRATE, MSW- DST	WISARD, WRATE, MSW- DST
Landfilling [6]	IWM, ORWARE, LCA- IWM, IWM-2, WASTED, EASEWASTE, WISARD, WRATE, WARM, MSW- DST	NA	NA	IWM, WARM, MSW-DST	IWM, LCA- IWM, IWM-2, WASTED, EASEWASTE, WISARD, WRATE, WARM, MSW- DST	NA
Transportation	IWM, ORWARE, LCA- IWM, IWM-2, WASTED, EASEWASTE, WISARD, WRATE, WARM, MSW- DST	NA	NA	NA	NA	NA

NA: Not Applicable
*Pre-combustion GHG emissions are those from the mining and transportation steps required to produce the fuels and materials used in the waste management processes. Combustion GHG emissions are those from the waste management processes directly. ORWARE seems to be the only model that does not consider pre-combustion emissions.
[1] With the exception of EASEWASTE, tools do not consider the energy and emissions from infrastructure production (e.g. collection vehicles and waste management facilities). In EASEWASTE construction of treatment and disposal facilities and materials used in waste handling can be part of the system if the user defines the material consumptions needed for construction and implements it under the facility.
[2] Estimated as Total CO2 fossil= total CO2 emitted- (total sequestered carbon * 44/12)
[3] Artificial fertilizers production and peat extraction.
[4] Assigns a displacement factor of 10% (Diaz and Warith, 2006).
[5] Considers a storage factor of 0.183 tonne of CO2 per tonne of organic waste (Diaz and Warith, 2006).
[6] CH4 emissions from landfills are counted even though the source of the carbon is mainly biogenic. The rationale being that the CH4 is created and emitted as a result of human activity. If the CH4 emitted from a landfill is recovered as biogas and then either flared or combusted to produce energy, the resulting CO2 is not counted. For anaerobic digestion, all the CH4 produced is typically combusted and so the resultant CO2 emissions are not counted.